Molten Salt Reacotrs

Jan Leen Kloosterman

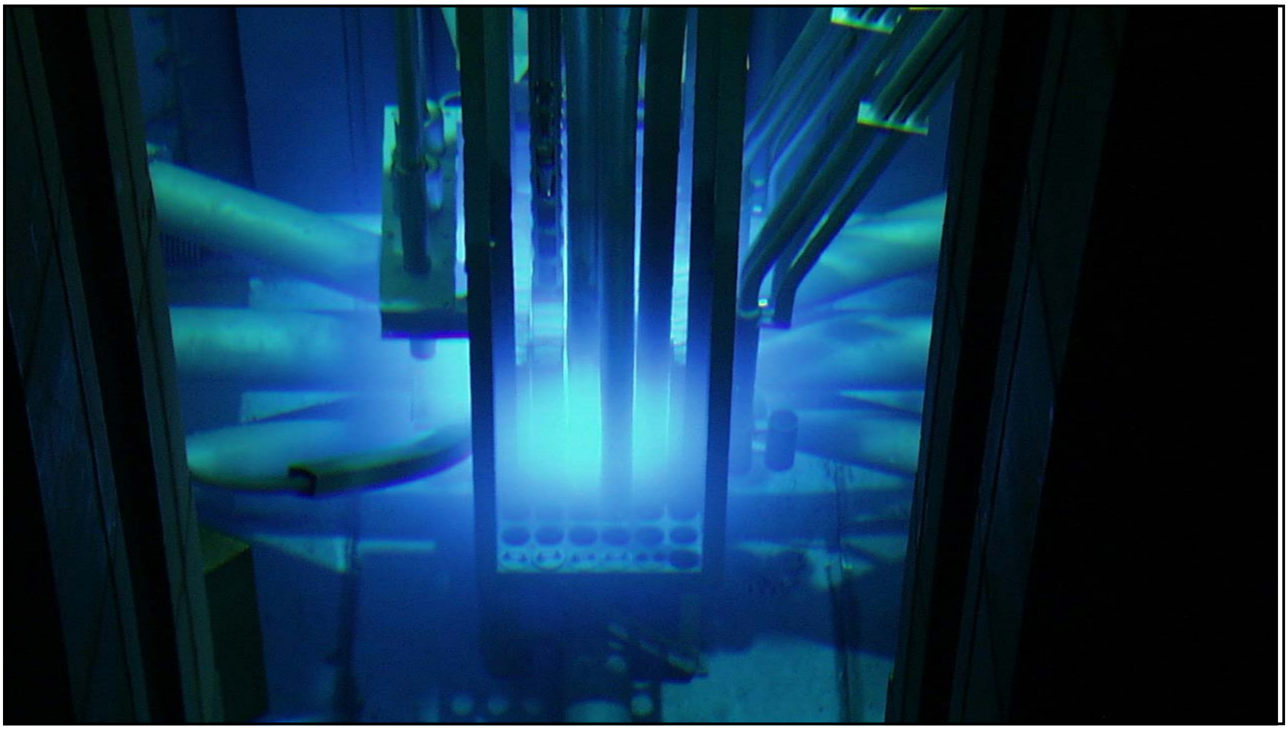
TU Delft

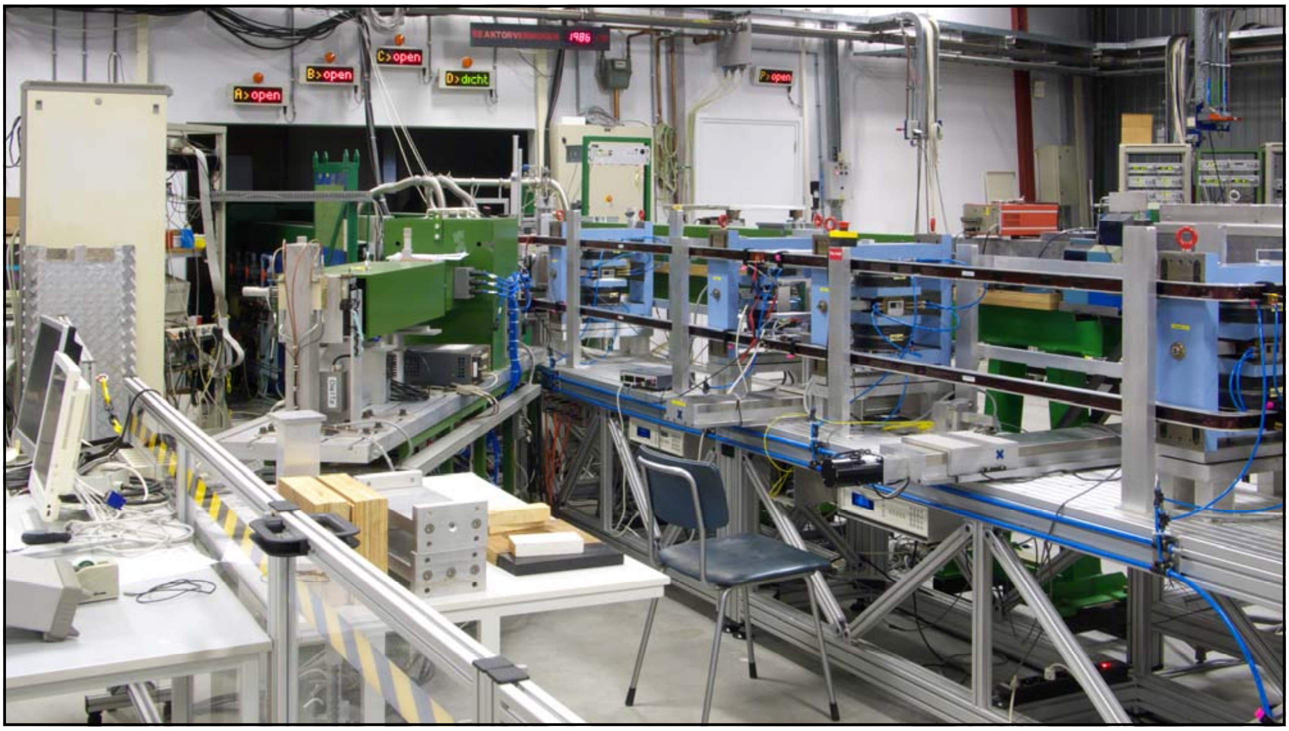
REACTOR INSTITUTE DELFT 1

The reactor and instruments

TU Delft

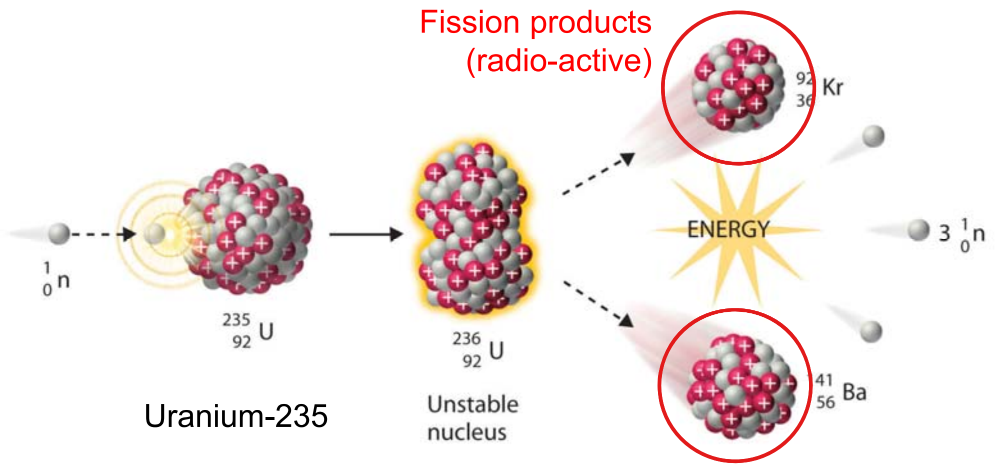
REACTOR INSTITUTE DELFT 2




A>open
B>open
C>open
D>dicht
1986

TU Delft

Nuclear fission



Chemwiki, CCPL 7

TU Delft

Nuclear fission

nuclide	#neutron	ΔM (MeV)	Change ΔM (MeV)	
U-234	142	-1731.5		-5.3
U-235	143	-1736.8	-6.5	
U-236	144	-1743.4		

TU Delft

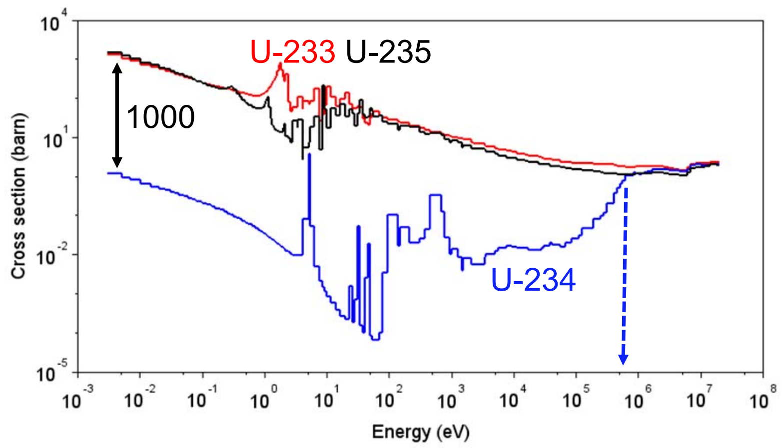
8

Nuclear fission

nuclide	#neutron	ΔM (MeV)	Change ΔM (MeV)	
U-233	141	-1724.7	-6.8	
U-234	142	-1731.5		-5.3
U-235	143	-1736.8	-6.5	
U-236	144	-1743.4		
Pu-239	145	-1758.9	-6.5	
Pu-240	146	-1765.4		-5.2
Pu-241	147	-1770.6	-6.3	
Pu-242	148	-1777.0		

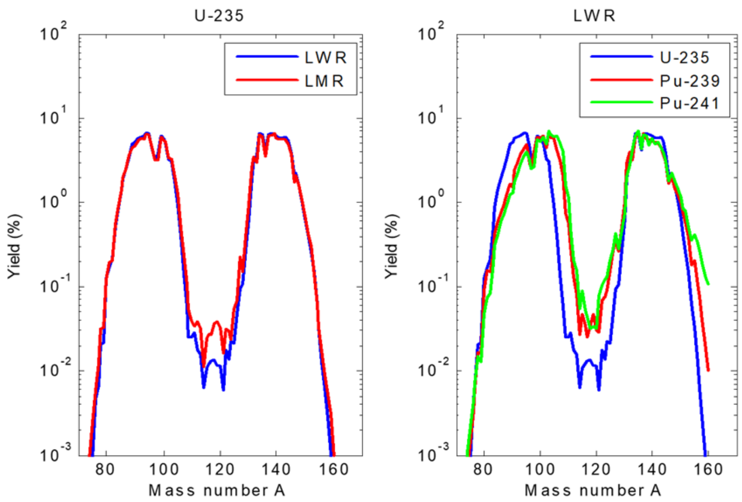
TU Delft

Fission cross section



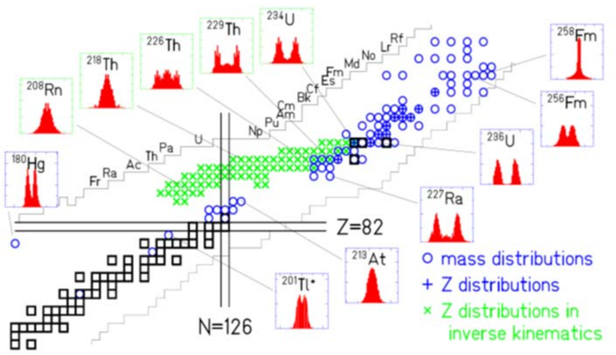
TU Delft

Fission product yields

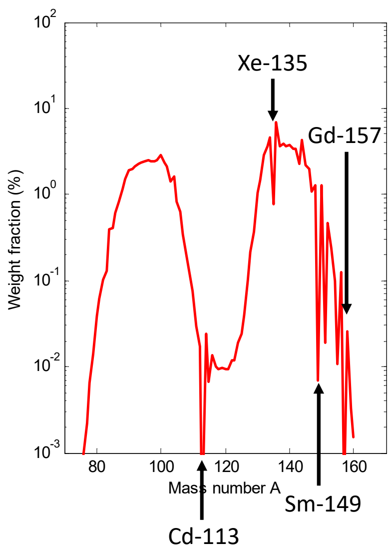


TUDelft

Fission product yields

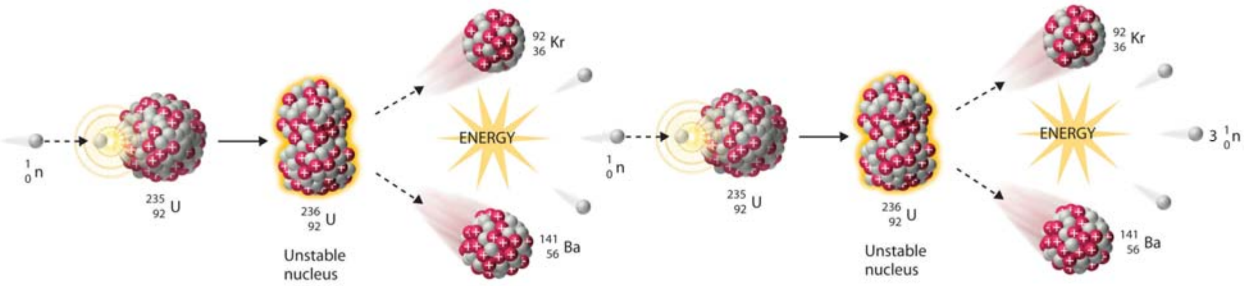


NEA/DB/DOC(2014)1



TUDelft

Fission chain reaction



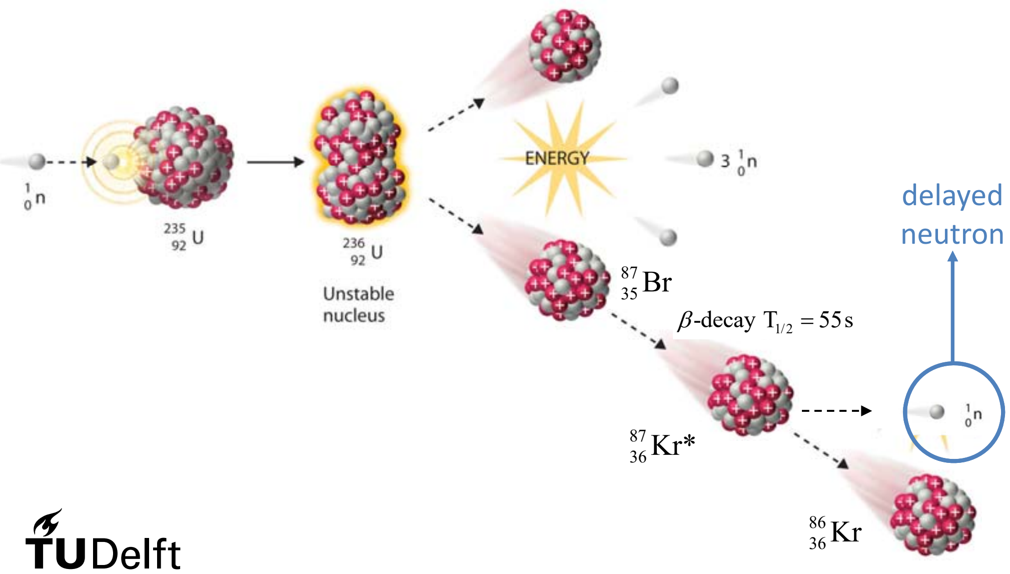
Chemwiki, CCPL

- Monitor and control fission chain reaction
- Extract the heat generated in the core
- Fuel and waste management

TUDelft

13

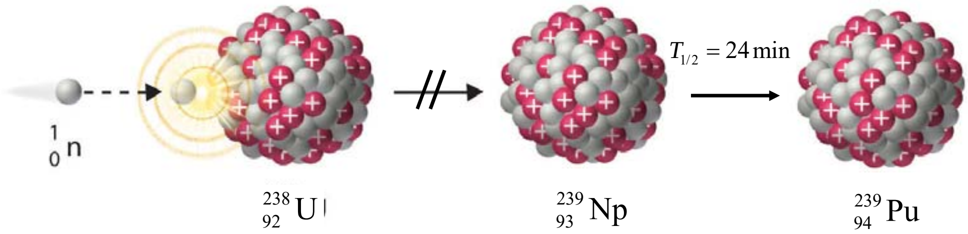
Delayed neutrons



TUDelft

14

Uranium fuel cycle

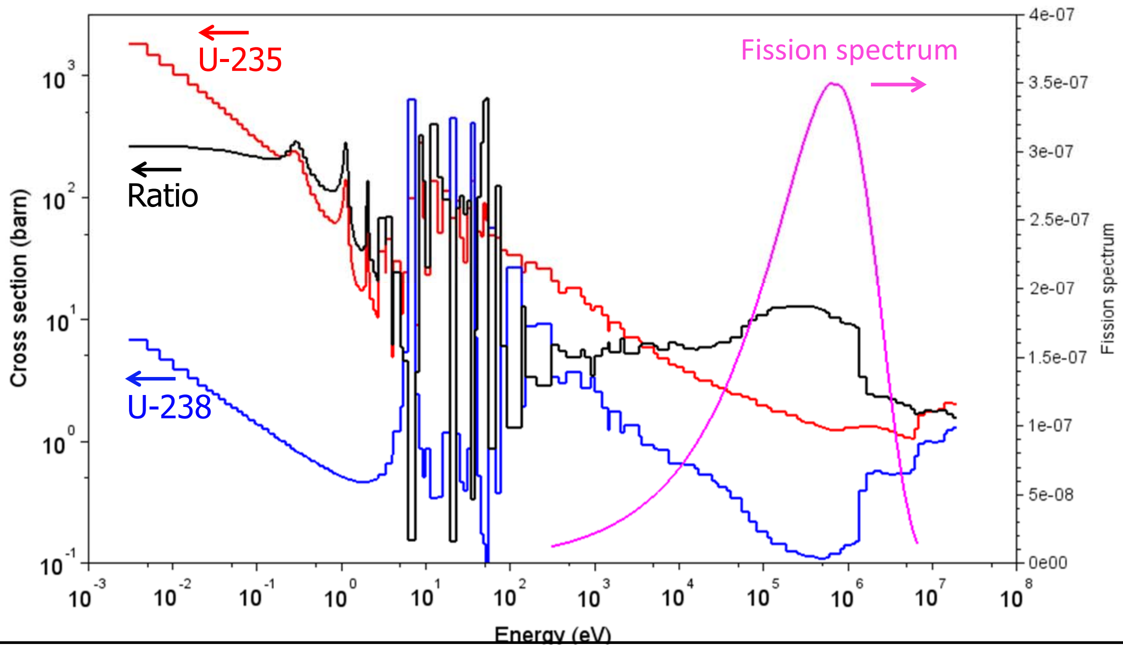


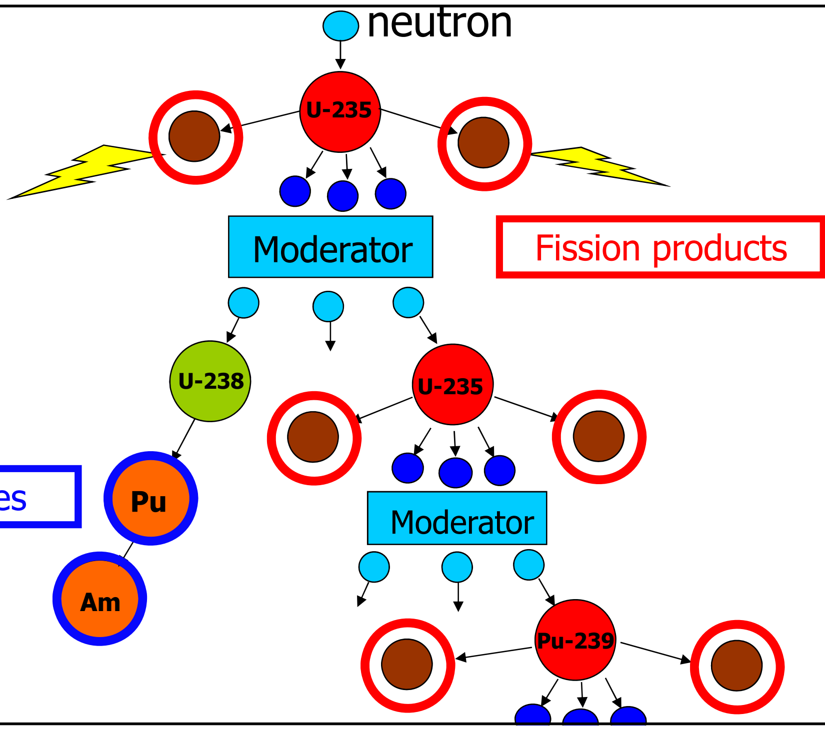
Uranium-238 Neptunium-239 Plutonium-239

TUDelft

15

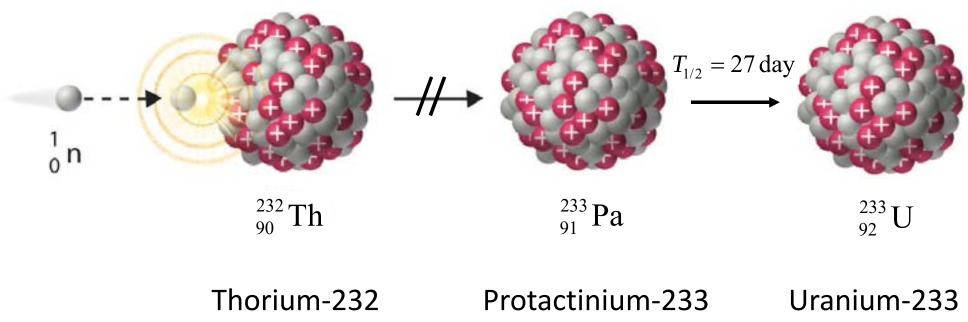
Absorption cross section





17

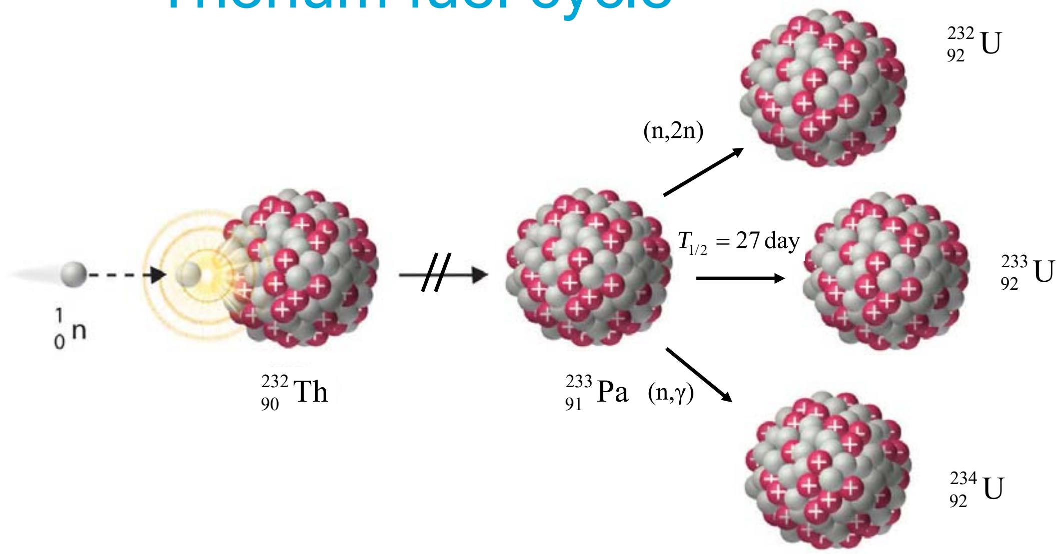
Thorium fuel cycle



TUDelft

18

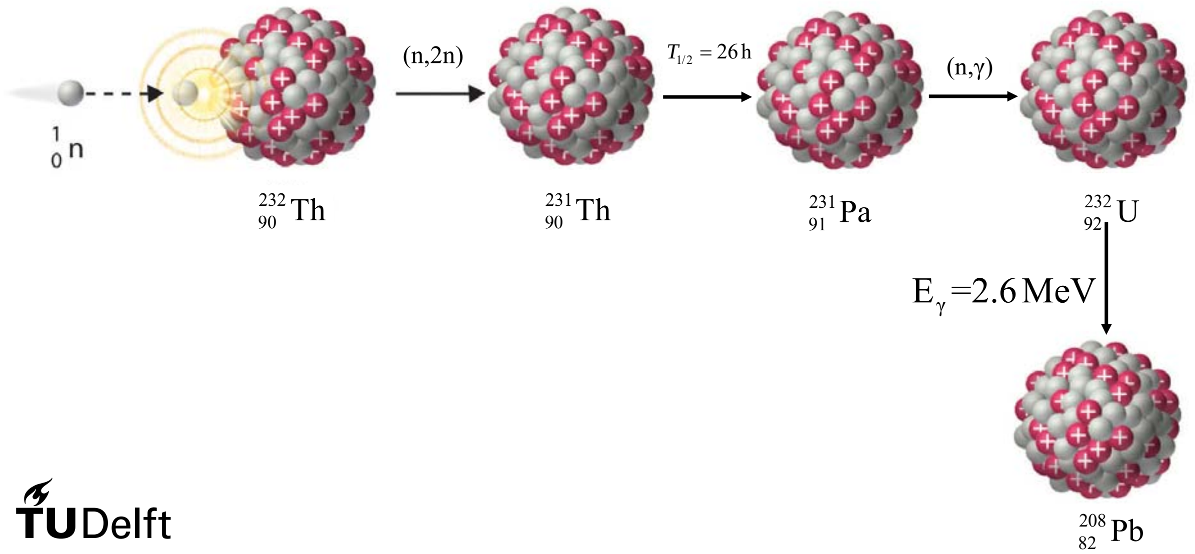
Thorium fuel cycle



TU Delft

19

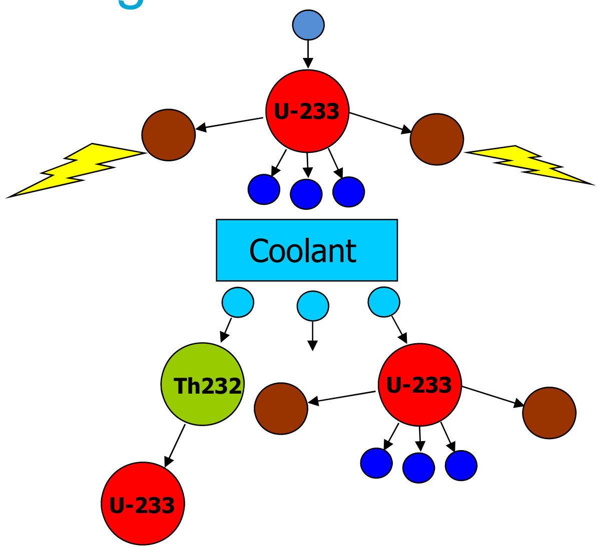
Thorium fuel cycle



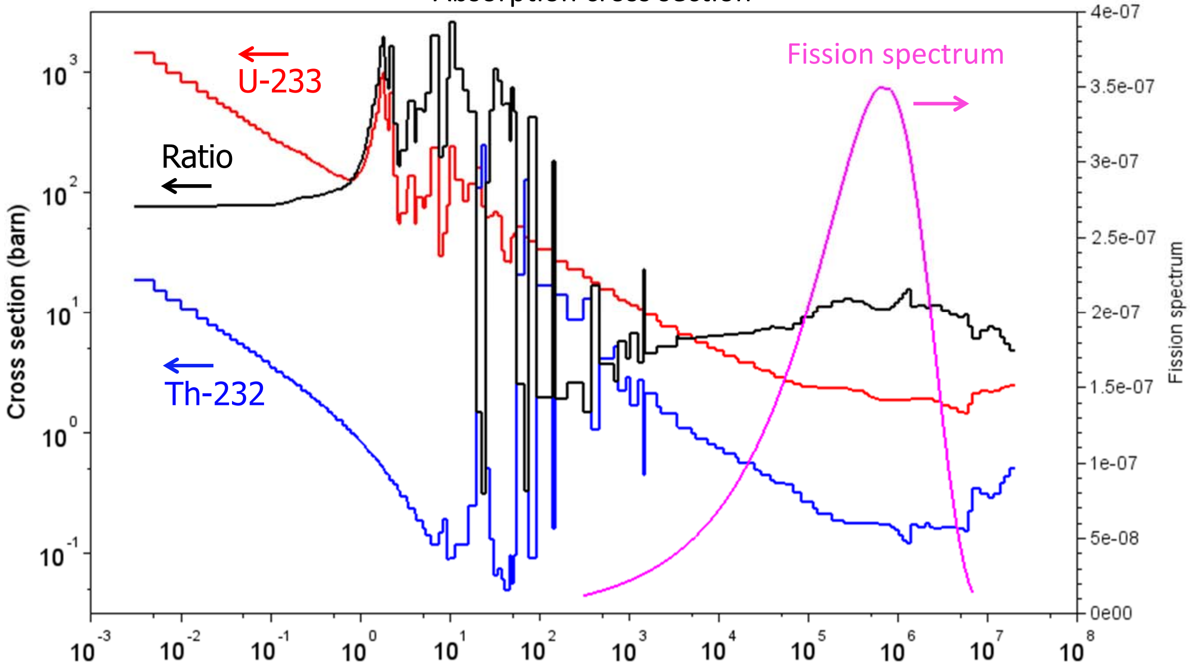
TU Delft

20

Breeding with thorium

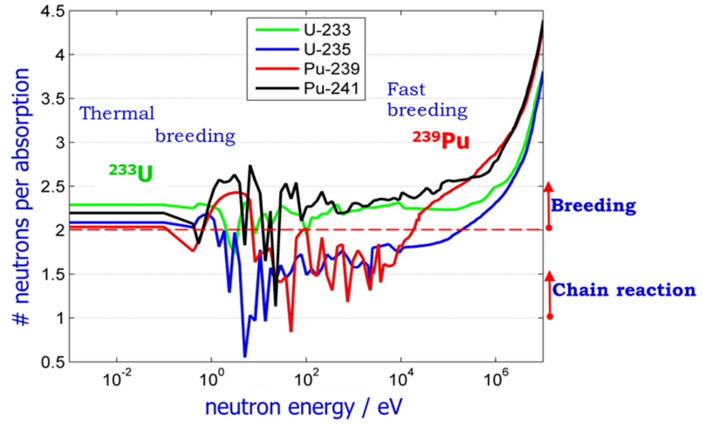


Absorption cross section



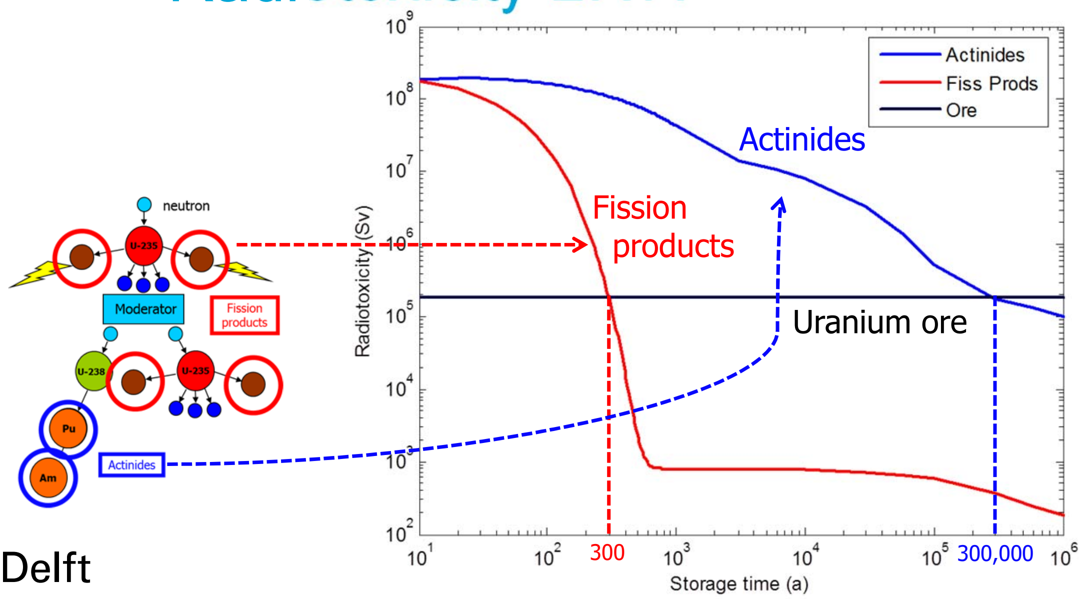
Thorium fuel cycle

$^{232}Th + {}^{1}n = {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$

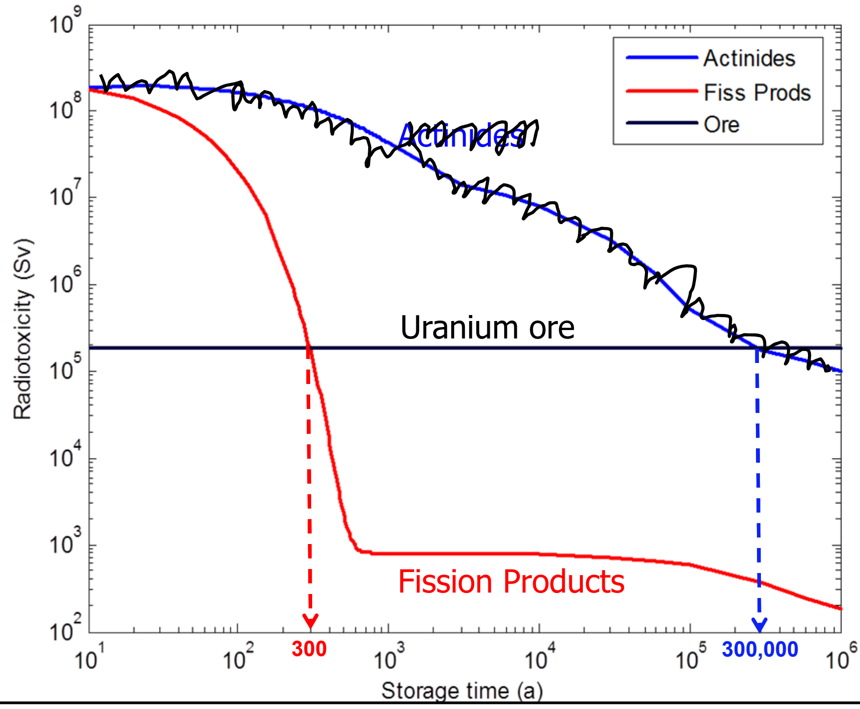


TU Delft

Radiotoxicity LWR

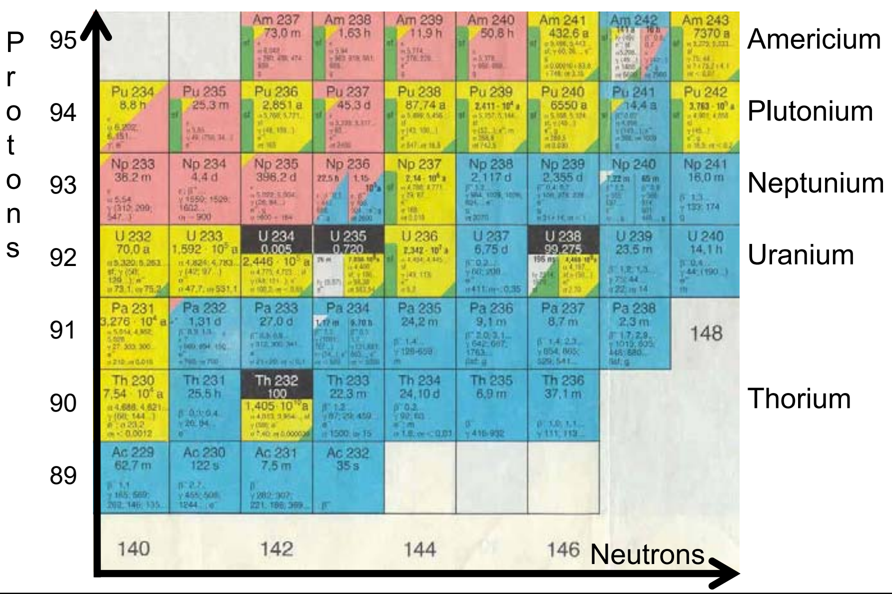


TU Delft



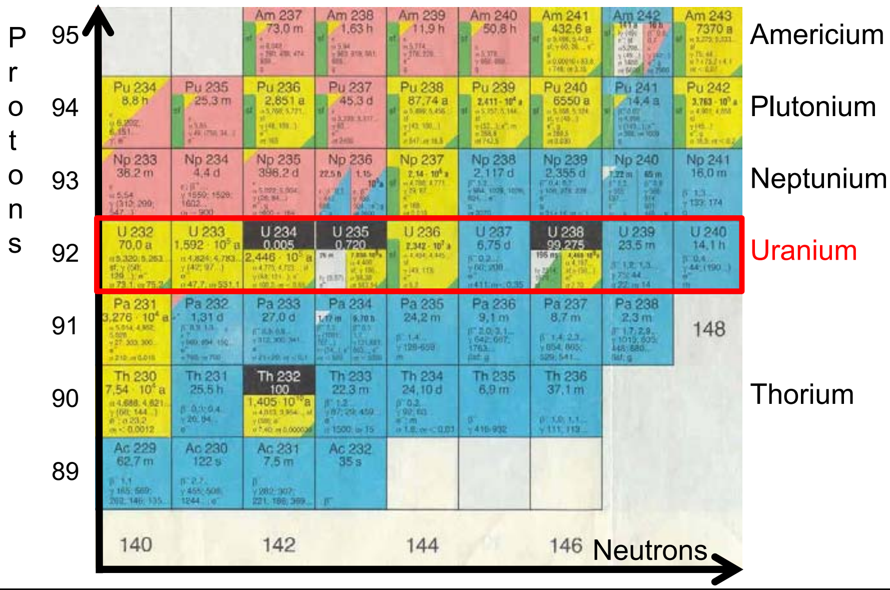
TU Delft

25



TU Delft

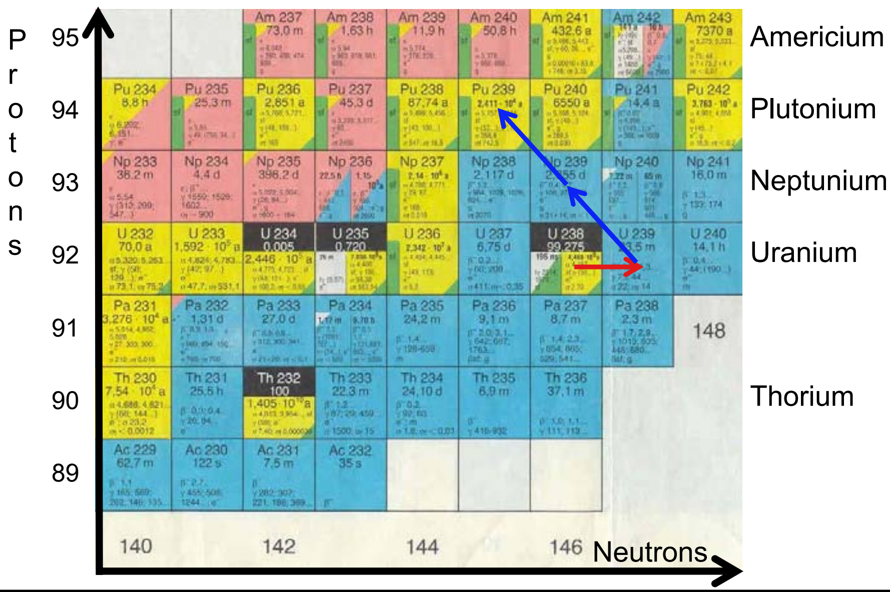
26



TU Delft

27

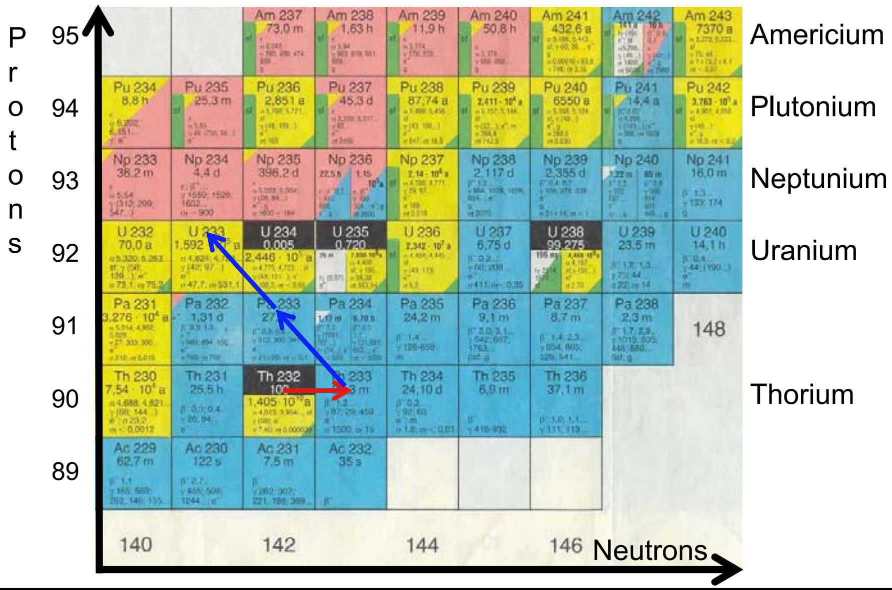
From uranium to plutonium



TU Delft

28

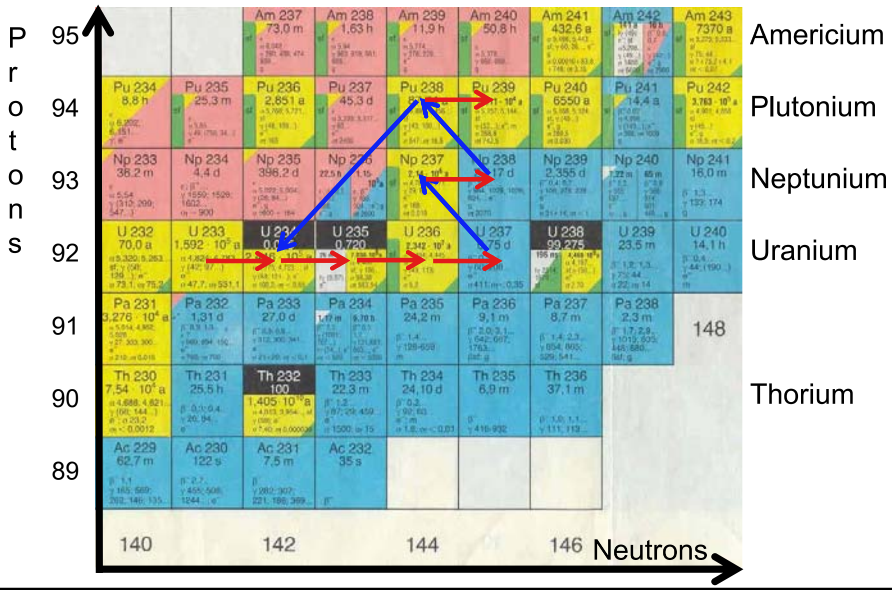
From thorium to uranium-233



TU Delft

29

From uranium-233 to plutonium



TU Delft

30

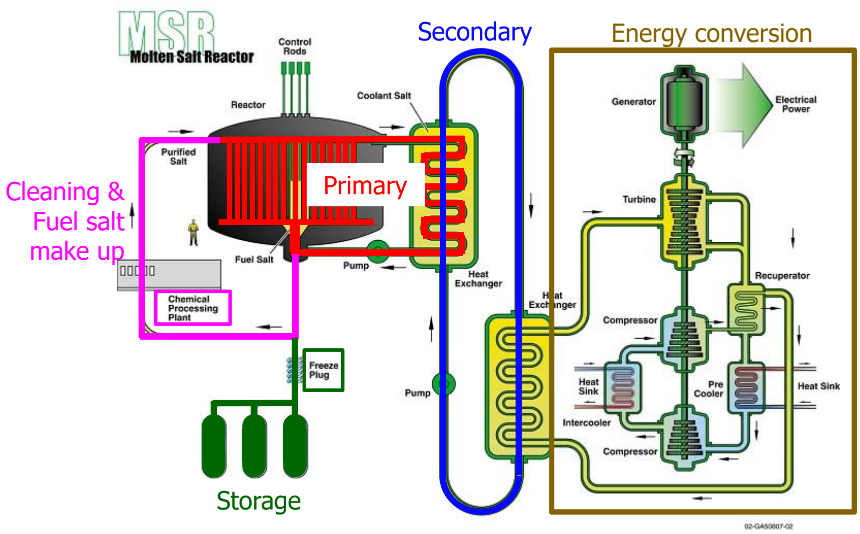
Thorium fuel cycle

- The absorption cross-section of ^{232}Th for thermal neutrons is three times that of ^{238}U
- The capture-to-fission ratio of ^{233}U is lower than for ^{235}U and ^{239}Pu in the thermal range
- The thorium fuel cycle produces less long-lived radiotoxic waste than the current fuel cycle
- Thorium based fuels *can* have intrinsic proliferation resistance due to their radioactivity. The gamma emission requires shielding and remote operations to handle the fuel.

TU Delft

31

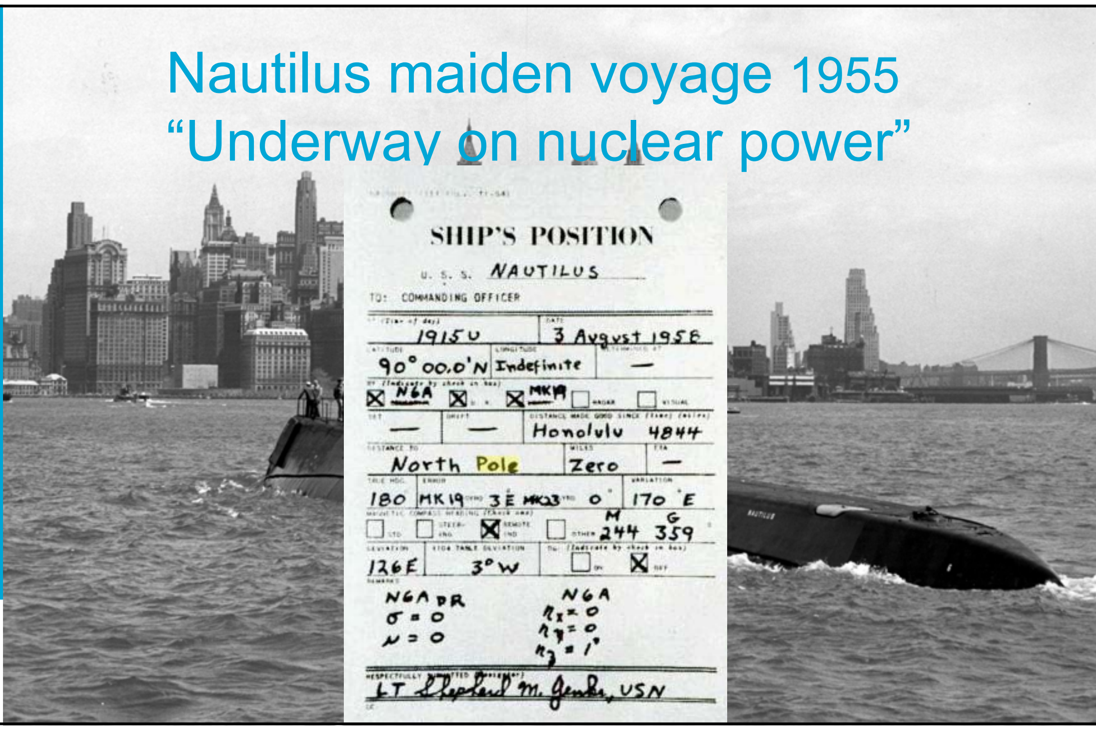
Molten Salt Reactor (MSR)



TU Delft

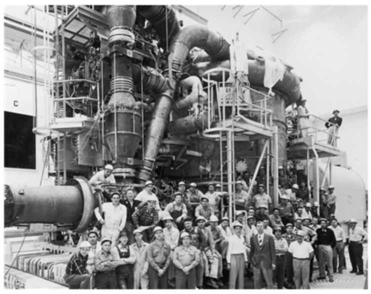
32

Nautilus maiden voyage 1955
"Underway on nuclear power"



33

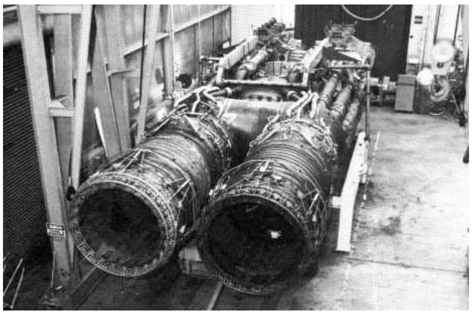
Heat Transfer Reactor Experiments 1 and 2 (1956)



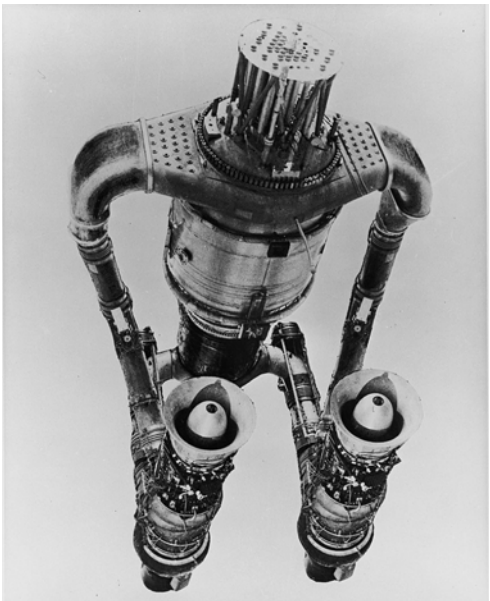
HTRE-1
(20 MWth)

34

Heat Transfer Reactor Experiment 3 (1958-1960)



HTRE-3
(30 MWth)



TU Delft

35

Hangar Aircraft Nuclear Propulsion program, Idaho

TU Delft

36

Alvin Weinberg
1915-2006

https://www.ornl.gov/content/alvin-m-weinberg-fellowship

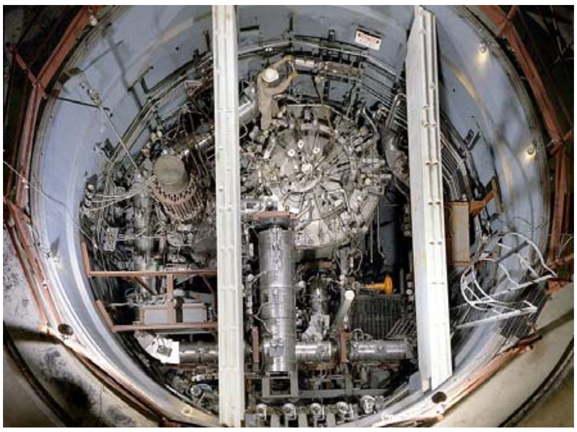
Alvin's 3P reactor
1952

https://en.wikipedia.org/wiki/Aqueous_homogeneous_reactor

TUDelft

wikimedia commons, GNU 37

Molten Salt Reactor Experiment
1965-1969



https://en.wikipedia.org/wiki/Molten-Salt_Reactor_Experiment

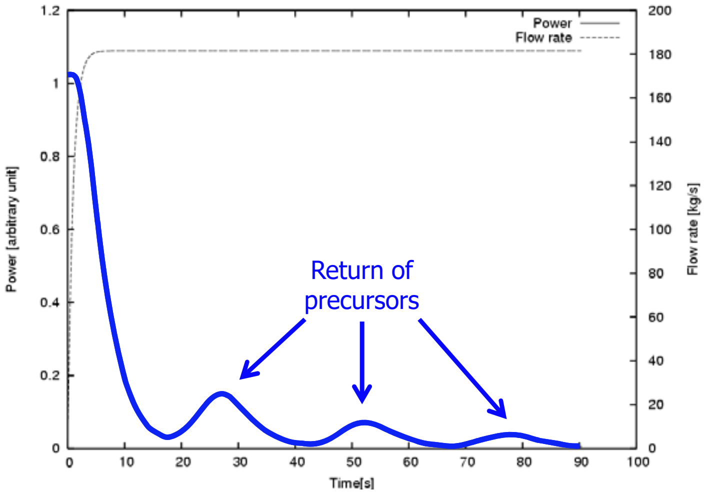
TUDelft

See movie: http://energyfromthorium.com/2016/10/16/ornl-msre-film/

38

MSRE Zero power pump start up

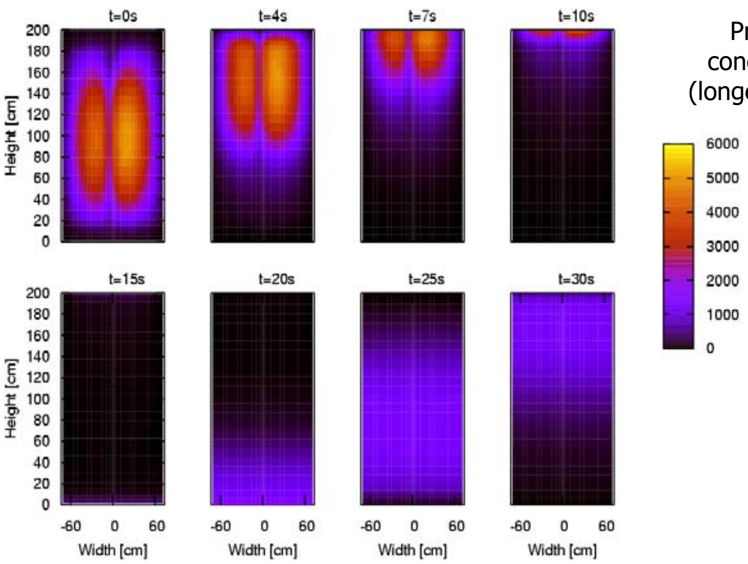
Pump start-up to 100%



TU Delft

39

MSRE: Zero power pump start up

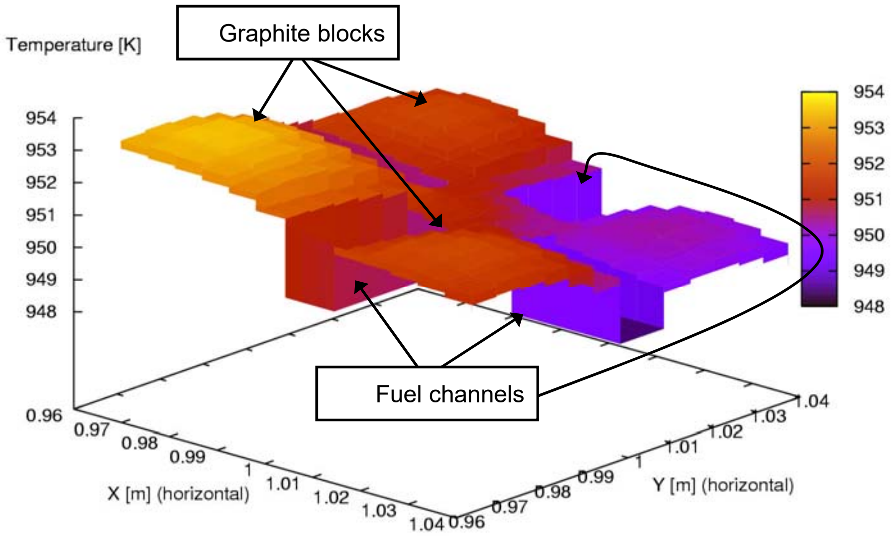


Precursor concentration (longest half-life)

TU Delft

40

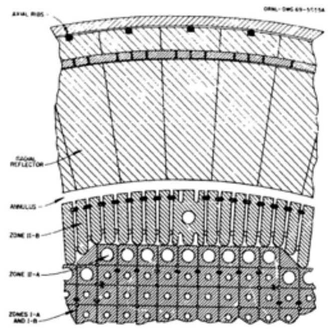
MSRE: Close up temperature field



TU Delft

41

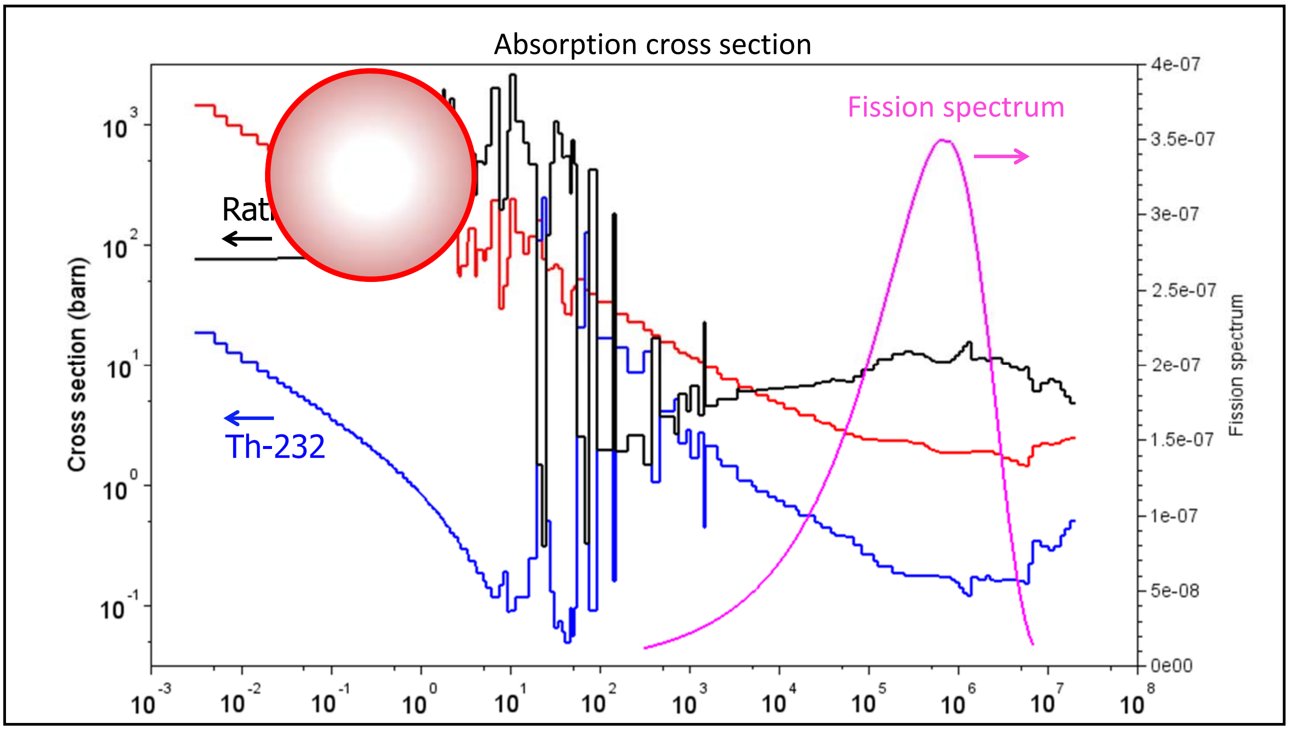
Molten Salt Breeder Reactor



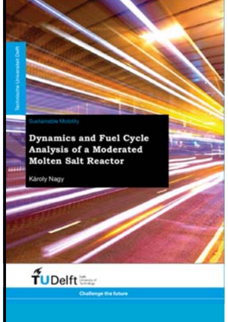
- ORNL design from the late 1960s
- 1000 MWe, breeder MSR
- Single fuel, single pass, moderated
- Salt composition: LiF-BeF_2-ThF_4-UF_4
- The project got cancelled in 1970
- The volume of the primary loop had to be processed in 10 days
- The global temperature feedback coefficient of the MSBR was positive

TU Delft

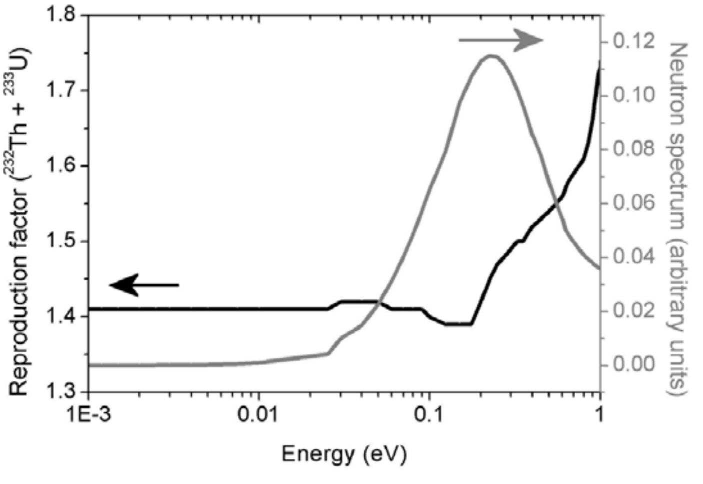
42



Positive temperature coefficient

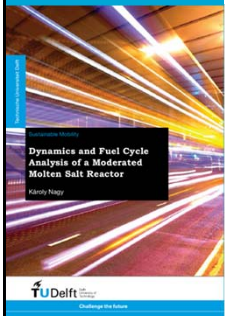


$$\frac{\nu\Sigma_f^F}{\Sigma_a^F}$$

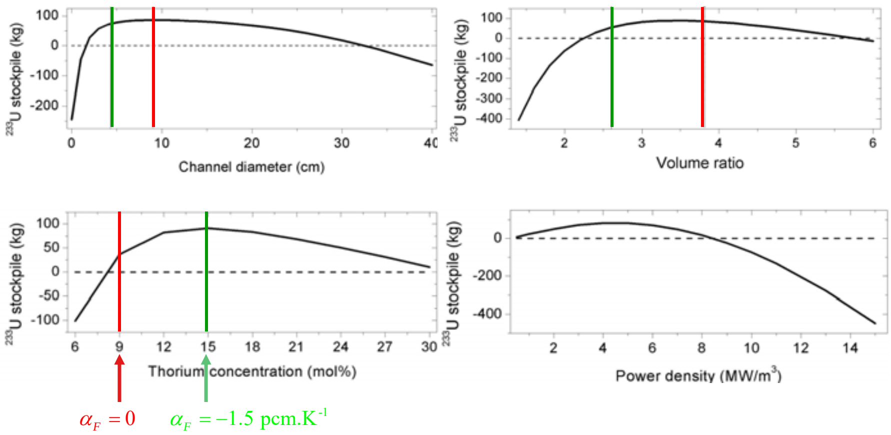


K. Nagy, Dynamics and Fuel Cycle Analysis of a Graphite-Moderated Molten Salt Nuclear Reactor, TU Delft, 2012

44

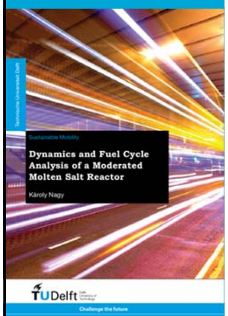


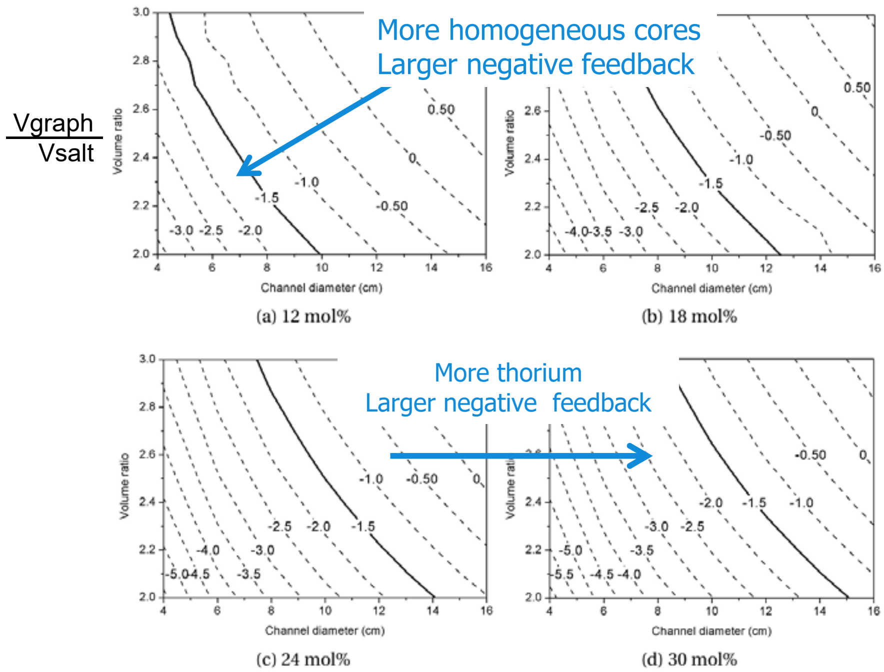
Effects of parameter variations



TU Delft

45

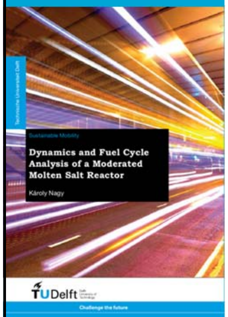




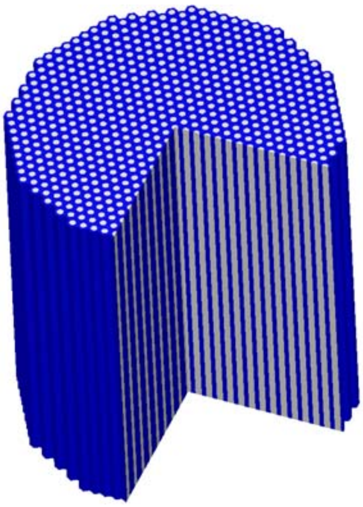
TU Delft

46

TUD-MSBR: Preliminary design



Vessel radius	3	m
Core radius	2.4	m
Vessel height	6.9	m
Core height	5	m
Plenum height	0.2	m
Number of fuel channels	1327	
Channel diameter	0.07	m
Salt composition	$LiF - BeF_2 - ThF_4 - UF_4$	
Thorium conc.	15	mol%
Mass flow rate	5395	kg/s
Length of primary loop	30	m
Power production	792	MW

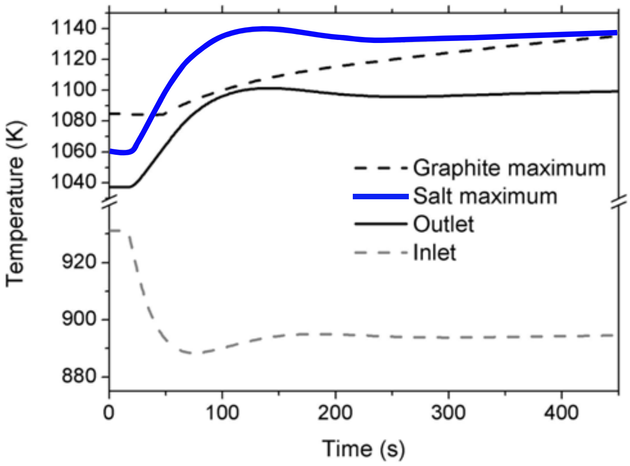


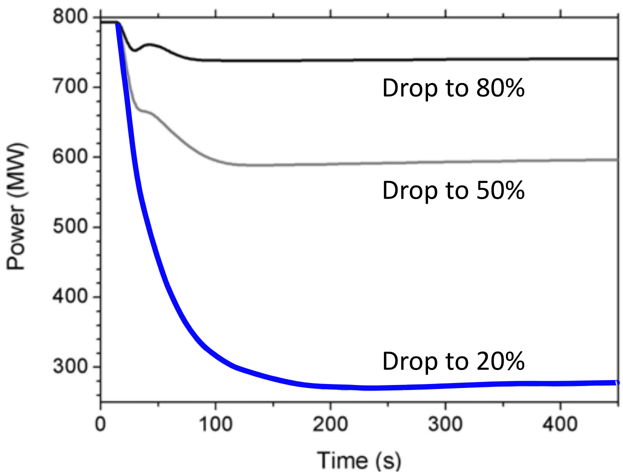
TU Delft

47

TUD-MSBR: Pump coast down

Pump coast-down to 20%





European SAMOFAR project

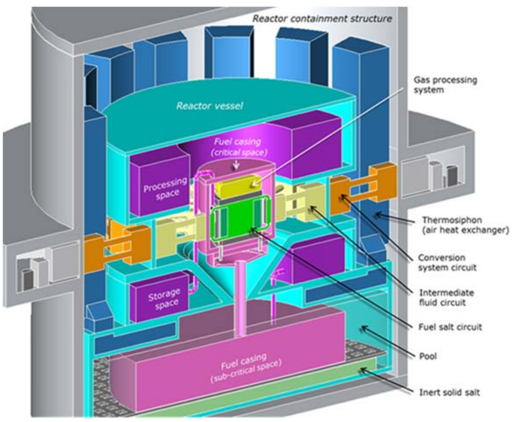
Safety analysis of the Molten Salt Fast Reactor

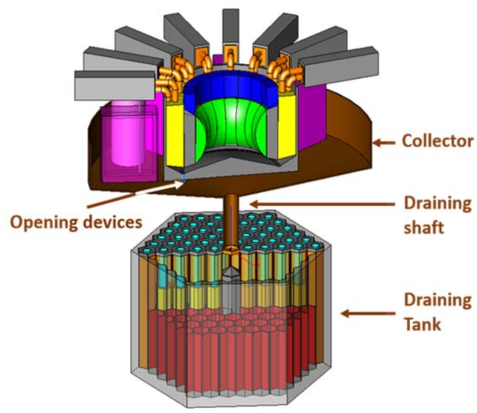
SAMOFAR

www.samofar.eu

49

Molten Salt Fast Reactor



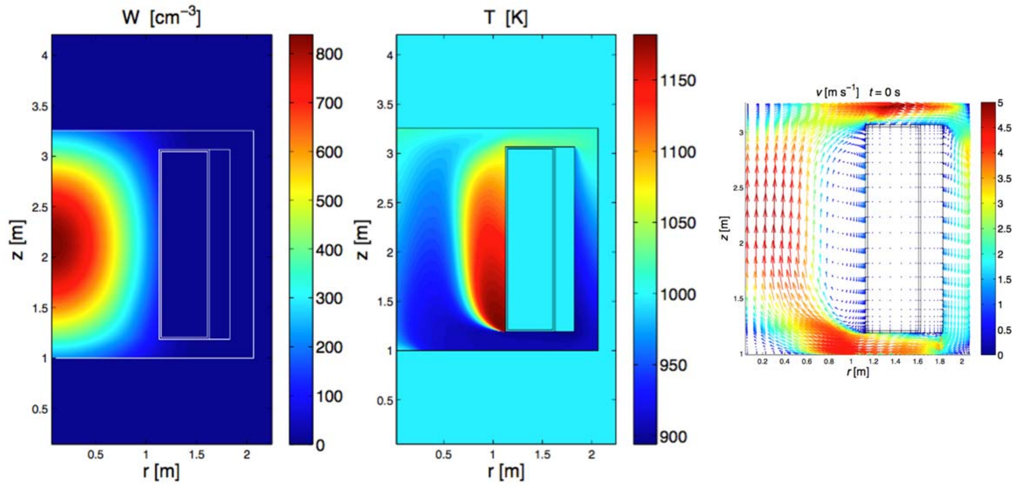


SAMOFAR

CNRS, Grenoble

50

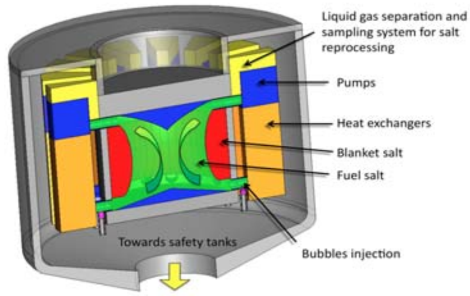
MSFR Operation conditions

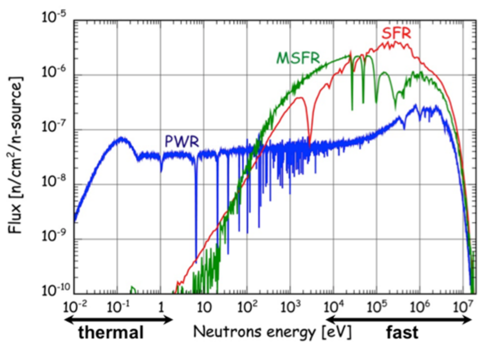


SAMOFAR

51

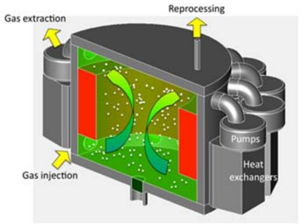
Thermal power	3000 MWth
Mean fuel salt temperature	725 °C
Fuel salt temperature rise in the core	100 °C
Fuel molten salt - Initial composition	LiF-ThF_4-UF_4-$(TRU)F_3$ with (77.7-6.7-12.3-3.3 mol%) and U enriched at 13%
Fuel salt melting point	585 °C
Fuel salt density	4.1 g/cm^3
Fuel salt dilation coefficient	8.82 10^{-4} / °C
Fertile blanket salt - Initial composition	LiF-ThF_4 (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient	-5 to -8 pcm/K
Core dimensions	Diameter: 2.26 m Height: 2.26 m
Fuel salt volume	18 m^3 (½ in the core + ½ in the external circuits)
Blanket salt volume	7.3 m^3
Total fuel salt cycle	3.9 s

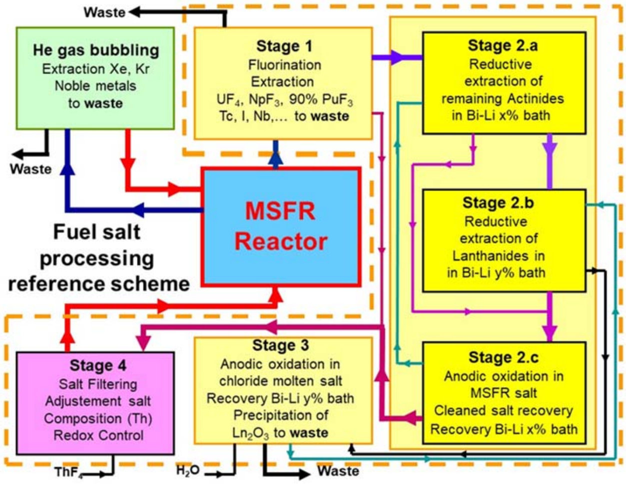




52

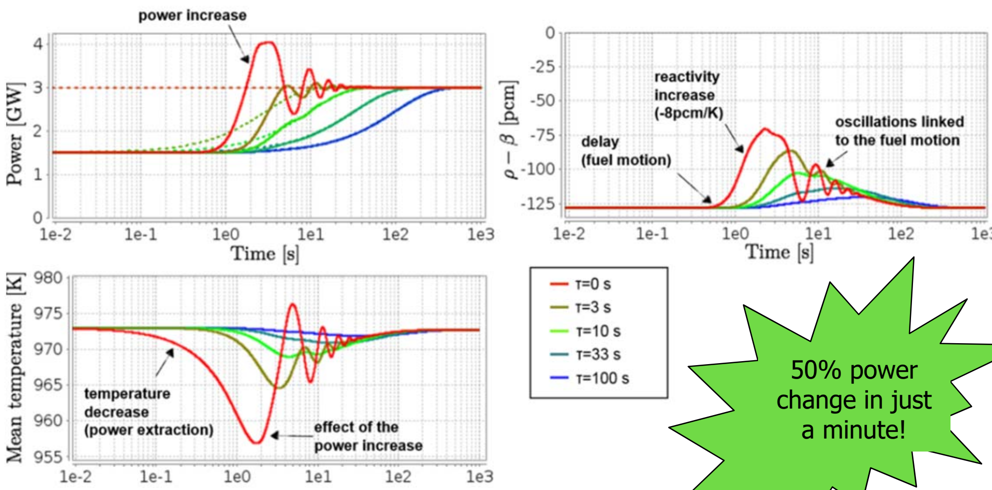
Salt processing steps





SAMOFAR

MSFR Load follow operation

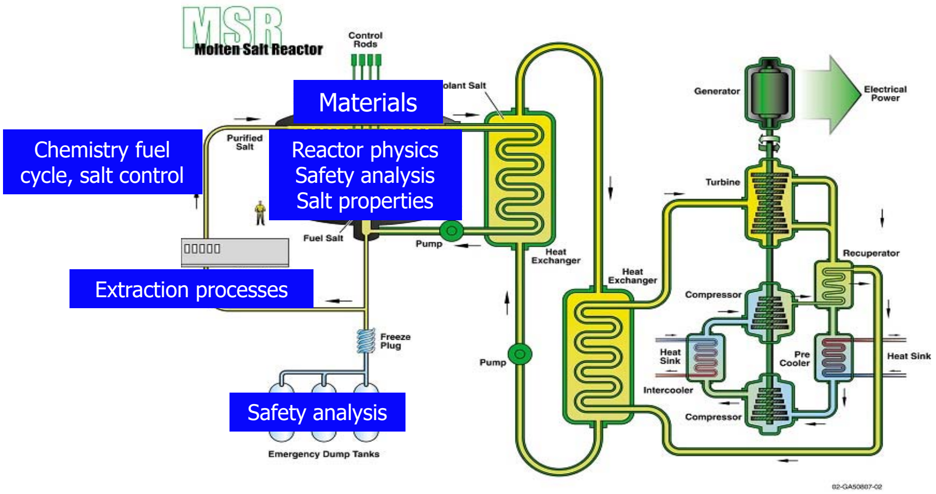


50% power change in just a minute!

SAMOFAR

Elsa Merle, CNRS, France

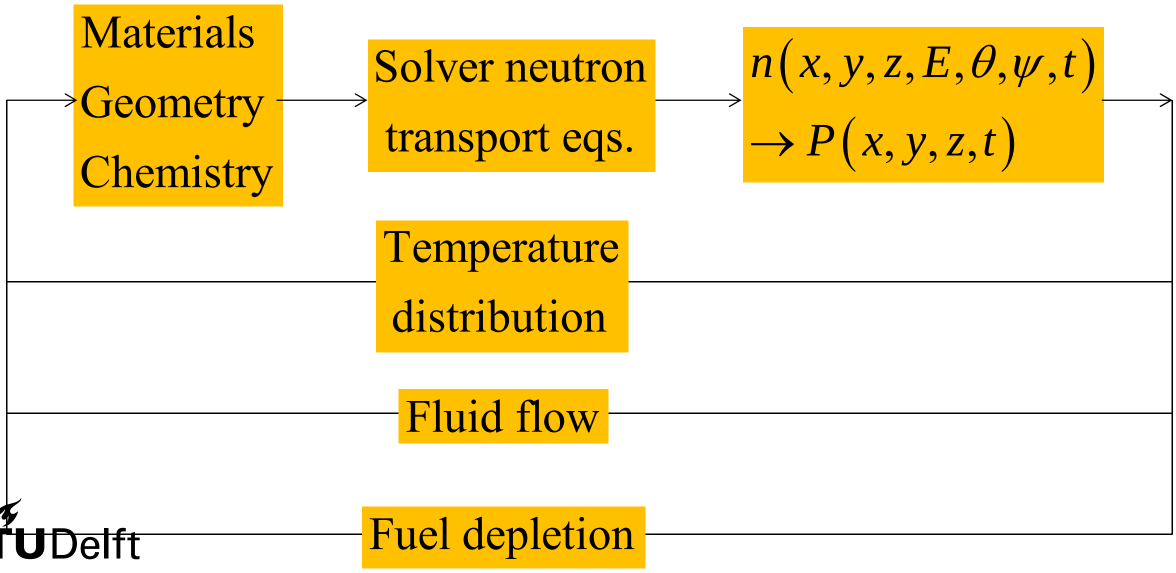
MSR research themes



TU Delft

55

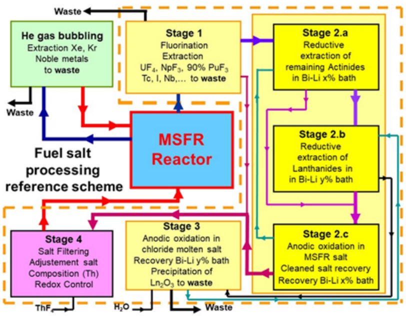
Simulation models

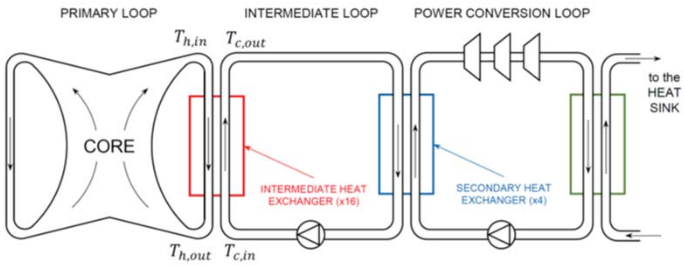


TU Delft

56

Simulation models





Fuel salt Processing ↔ Core physics ↔ Energy Conversion System

TU Delft

European SAMOSAFER project

Simulaton Models and Safety Analysis for Fluid-fuel Energy Reactors

Logo?

Start up companies

And more ….

TU Delft

59

MSR concepts

- SINAP: Thorium Molten Salt Reactor-Liquid Fuel (TMSR-LF)
- Terrestrial Energy: Integral Molten Salt Reactor (IMSR)
- ThorCon: Transportable units
- Moltex: Stable Salt Fast Reactor (SSFR)
- CNRS/SAMOFAR: Molten Salt Fast Reactor (MSFR)
- Kurchatov Institute: MOSART
- Dual Fluid Reactor (DFR)
- Terrapower: Chloride-salt fast reactor
- Flibe Energy: Liquid Fluoride-salt Thermal Reactor (LFTR)
- Copenhagen Atomics: Atomic Waste Burner (ATW)
- Seaborg Technologies: Molten Salt Thermal Waste burner
- Elysium industries
- …..

TU Delft

60

Conclusions

The Molten Salt Reactor has the potential to excel on

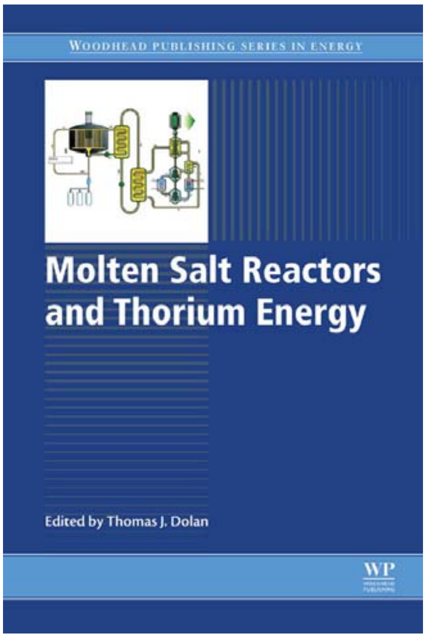
- Safety
- Sustainability
- Flexibility (fuel cycle, operation, size, …)

But:

- Development requires large R&D efforts in many fields (materials, salt chemistry, physics, safety, experimental validation, …)
- Licensing, non-proliferation, economics, and other topics are not a done deal

TU Delft

61



TU Delft

62